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ACTIVE BENDING STARTING ON CURVED ARCHITECTURAL SHAPE

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Summary. This paper describes the implementation of an analysis technique for active bending beams starting on a rough curved architectural system.

1 INTRODUCTION

In earlier applications active bending analysis started with a straight beam that was bend to a curved one. In this paper we show the technique starting with a curved architectural shape (see Fig. 1 left) and giving the beam the information that it originally was straight. So an internal bending prestress can be calculated and applied that corresponds to the input curvature of the beam chain.

In this paper we demonstrate the technique and check it by removing the membranes and fixings and let the beams relax. Then they must go back to an unstressed straight beam again.

Special focus is set on problems of torsion in active bending structures.

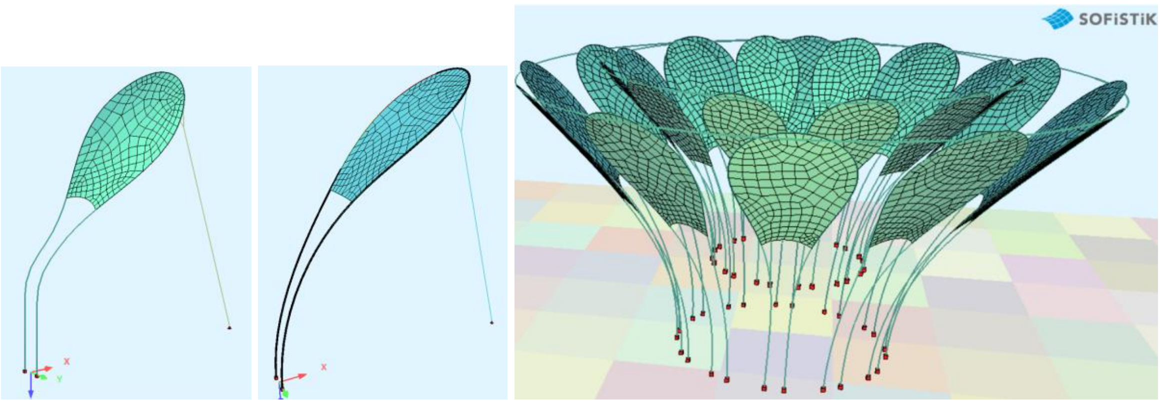

Figure 1: Leave : rough input system – activated bending - multiple leaves added to an ensemble

2 SIMPLE BEAM

In earlier applications a straight beam was bent in a geometrical nonlinear analysis TH3 into a curved shape [1]. As a restult, we got a stressed bended beam, see Fig. 2:

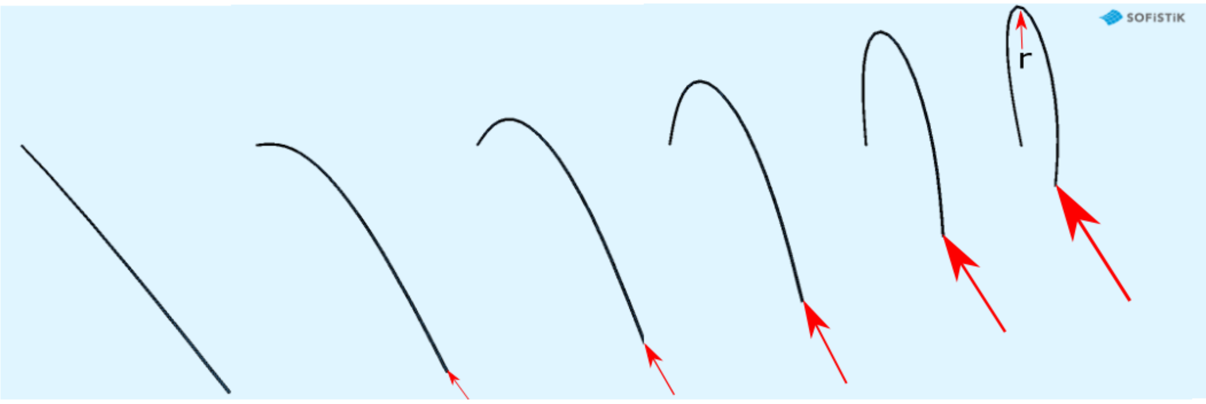

Figure 2: Bending up a straight beam

A new function ACTB uses another much easier way. The system is already input curved and you only give the beam chain the information that it originally was straight. In a first step the program calculates the curvature of the curved input beam chain and then applies an internal bending prestress that corresponds to this input curvature. This prestress would like to bend back the beam chain into a straight shape.

The input shape must not be totally correct. The beam will push itself automatically into an equilibrium active bending shape. In the following picture the beam behind is the just up-bended beam (group 1), the middle beam (group 2) has already got the final input shape in SOFIMSHA, the front beam (group 3) starts with a circular input geometry. In Fig. 3 left we see the result without ACTB input, then group 2+3 are stress-free. The result with input ACTB for groups 2+3 is shown on the right. Then all three beams end in the same stressed shape and bending moment as shown in Fig. 4.

Figure 3: Left system without ACTB, 3=circular input system, on the right result with ACTB

As a check we then remove the supports and let the beams *relax* freely (slow removal including dynamic relexation). Then we get three straight beams again, see Fig. 5 - as it must be, although two of them were input with curved geometry!

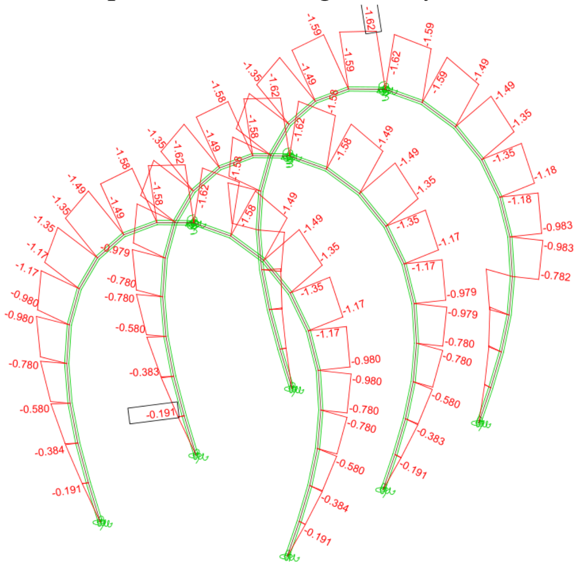

Figure 4: Bending moments are identical! -> ACTB works correct.

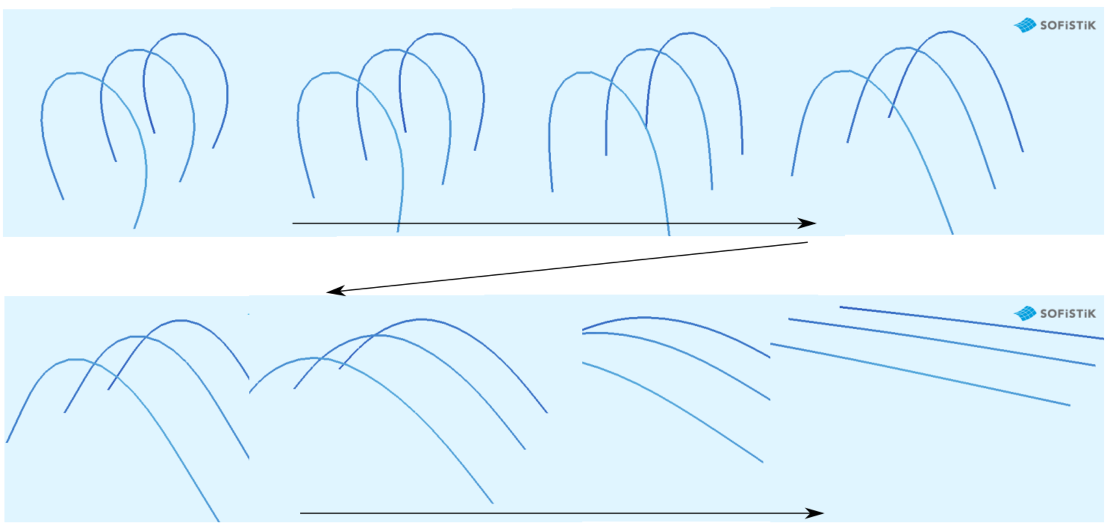

Figure 5: Relaxation by smoothly removing the supports

3 TORSION

3.1 Torsion case study

If we bend a straight beam with a cable into an active bending shape and then apply a horizontal force at the cantilever, we would first think a torsional moment at the bottom support is generated, see Fig. 6. The example is taken from [2].

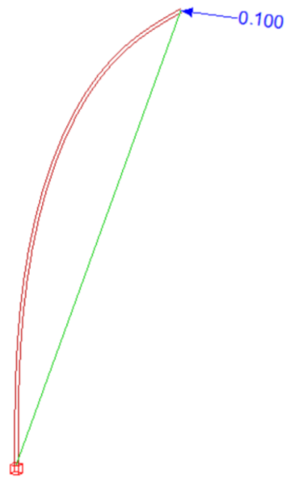

Figure 5: Torsion case study

In the following we demonstrate, that no torsional moment will appear in this case. Please notice that we can also start to bend the beam backward or under 30 degree, see Fig. 6.

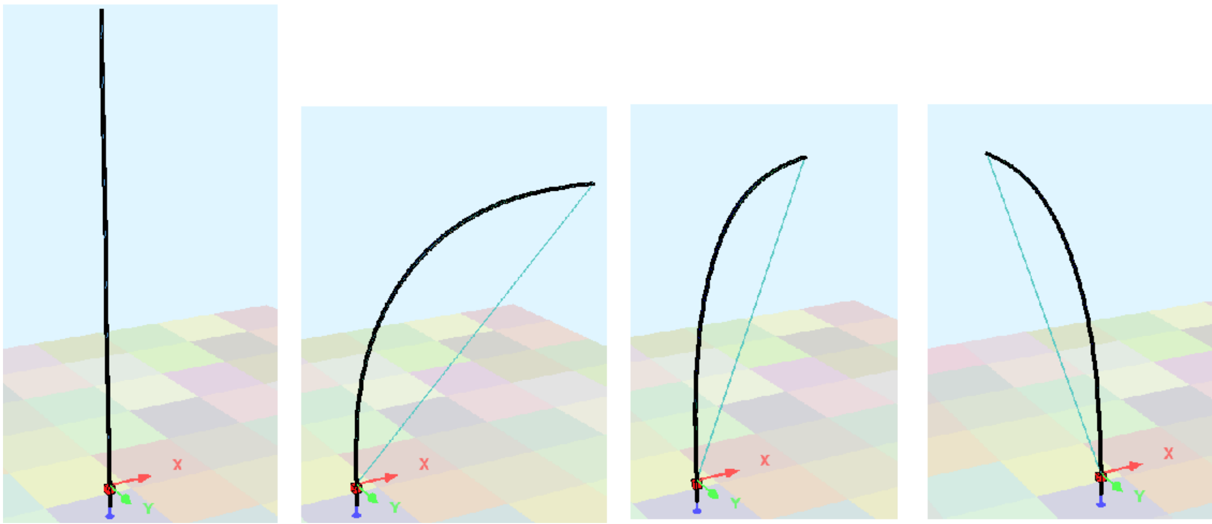

Figure 6: Torsion case study: left starting system, then bend to +x, under 30 degree or backward (-y)

The amount of energy is the same for all three cases. Therefore a horizontal deformation of the cantilever should not activate additional energy in the system. But this would mean that the system is unstable regarding rotation around the z axis. But the beam is fixed at the bottom - so this should not be the case.

But it is - with a horizontal deformation the beam just rolls away without a force into the new position, see Fig. 7 (at least theoretically). This happens for a perfect round beam, while the cable must be attached at the cross section center of the beam. In reality a beam is never perfect round - it will always bend into a favored direction.

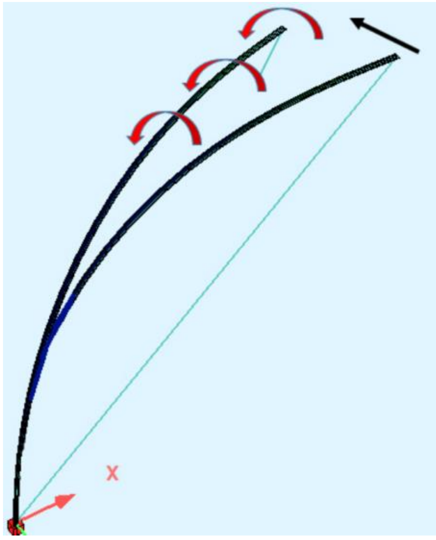

Figure 7: Horizontal deformation of the cantilever - the beam just rolls away without force

We (the SOFiSTiK team) have build a real model and proved that the beam really rolls away and no torsion appears, see YOUTUBE video with search term 'active bending torsion beam':

Figure 8: torsion test case - YOUTUBE video 'active bending torsion beam'

You can also compare the behavior with a tube-cleaning-spiral that you twist at one end. Also in case the spiral goes around in curves, you can twist it nearly without effort if the end of the spiral and the spiral in between is not fixed against rotation.

Conclusion: on many deformations and loadings an active bending beam just rolls away or rotates and withdraws itself from torsion.

3.2 Torsion on beam with fixed ends

So we use a beam with restrained ends in the next example according Fig. 8 - then we can introduce a torsion. To test it, we first bend the straight beam to a half circle (also requires bending moment at the end of the beam) and then apply torsion. Accordingly, we rotate the left support left and the right support also left. As a result we get a constant torsion in the beam.

Under torsion, little horizontal deformations occur vertical to the circle plane. If we now freeze the system and store it (SOFiSTiK-ASE: SYST STOR YES) and then start the active bending procedure ACTB on the stress-free updated system, we get a torsion in the beam - as in the original system. In the active bending routine this is created with a rotational check that recognizes a torsion via the little horizontal deformations. You only have to tell the program that the active bending beam is restrained at both ends and that at both ends torsion can be applied (SOFiSTiK-ASE: ACTB MEND 'FIX' MT 'FIX'). Otherwise, ASE assumes that the beam does not have bending or torsional moments at both ends - as in the first example.

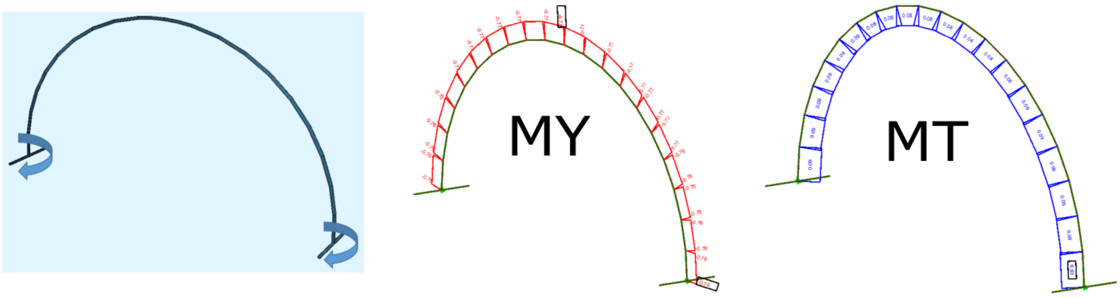

Figure 9: left: bend up a straight beam to a half circle and torsioned : center: MY right: MT

3.3 No torsion in case of constant beam rotation

If we rotate both ends in opposite direction, so the left to the left and the right to the right, we can rotate the beam without energy. The whole beam just rotates away, see Fig. 9. This happens because the active bending beam originally came from a straight beam and the stress-free length of the inner fiber has the same length as the outer fiber.

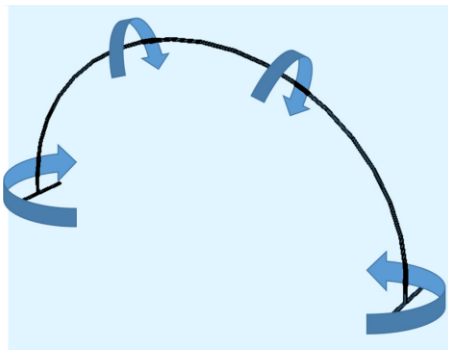

Figure 10: Bend up a straight beam to a half circle and torsioned contraverse: no torsion MT appears

This would not happen in case of a stress-free half circle - it has a shorter inner fiber and a longer outer fiber. A torsion would require energy. So again we see: it is not so easy to get torsion into an active bending beam.

3.4 Torsion caused by loading transverse to the main active bending plane

If we take the stressed system from the previous chapter and apply a horizontal force on top, see fig. 1, the load and the induced shear force acts transverse to the main active bending plane and we get a torsional moment MT. Depending on the torsional restraint at the bottom the system is more or less flexible for this transverse loading.

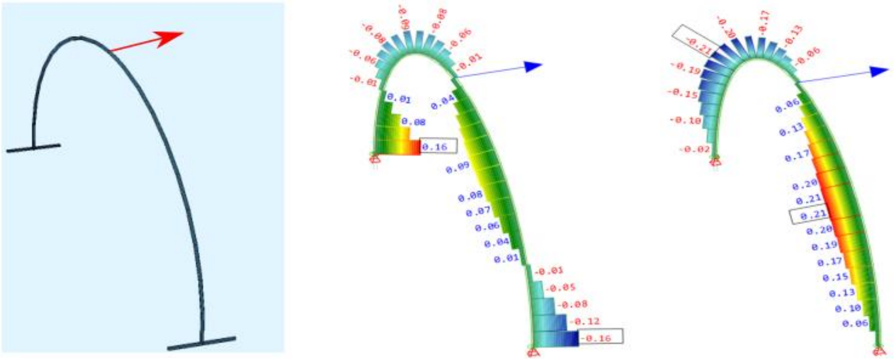

Figure 11: MT for loading transverse to main plane: middle full, right torsionfree bottom fixing

But the material stress is often small compared to the bending stress. In the example of fig. 12 max-tau-MT is less than 0.1\% in relation to the maximum bending stress.

4 ACTIVE BENDING INCLUDING A MEMBRANE

In the next example similar to [3] we start only with a rough desired architectural form in a graphical input (AUTOCAD-SOFIPLUS) and immediately insert a formfinding membrane. The curvatures must not be exact in this input system. So the upper part with the membrane was input in a 45 degree plane to have an easy input, see Fig. 12:

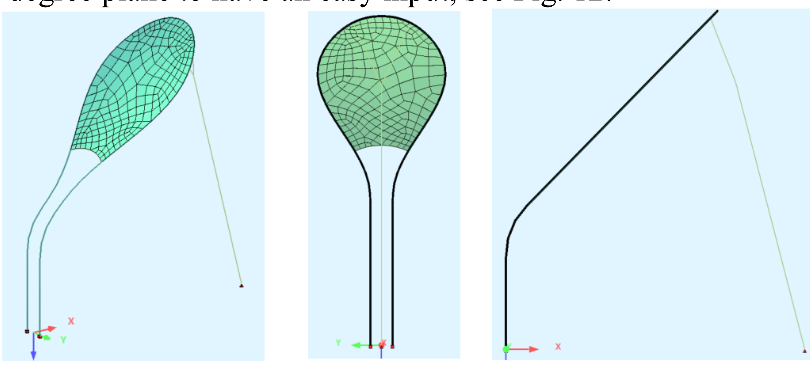

Figure 12: Input system: center: viev in x, right: side view (straight membrane input plane)

With the special input ACTB, we specify now that the beam originated from a straight beam and so the system nearly playfully iterates to its stability shape. Due to the bottom restraint, the beams pull up and tension the anchorage cable. As the membrane is defined as a soap film with given prestress, it finds a stress-constant form as well, see Fig. 13. The bottom cable of the membrane can be input with a given length.

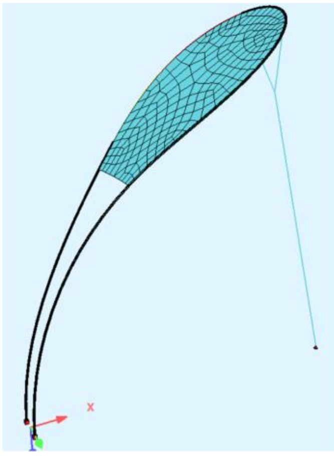

Figure 13: Result of formfinding with ACTB GRP 2 (beam elements)

Torsion: caused by the anchorage cable a slight torsion is induced compared to fig. 11. Max-tau-MT is less than 0.1\% in relation to the maximum bending stress. Depending on the torsional restraint at the bottom the system is more or less flexible against this horizontal loading of the anchorage cable.

To check if the active bending moment is correctly introduced in the curved input system, we now let the beam relax. For this we switch off the membrane and the cable and cut the beam into shorter pieces. With this we start a dynamic relaxation and as a result we really get straight pieces, see Fig. 14:

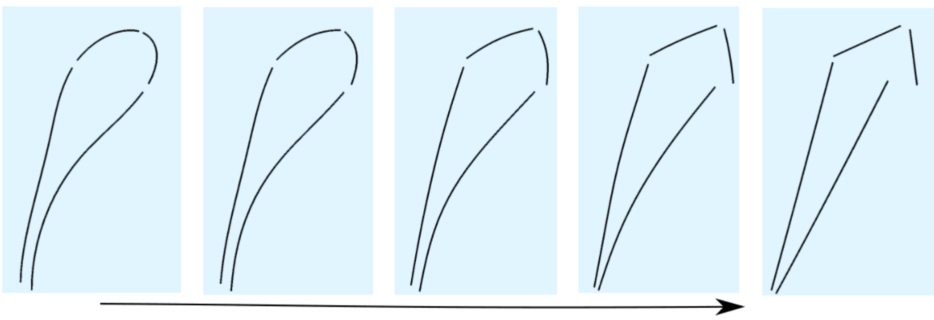

Figure 14: Dynamic relaxation to check if straigth beams remain

The system is rather flexible and would swing or flutter on wind. Without wind it is stable, but the first buckling eigenfrequency is only a little bit greater than 1.0. Now it is easy to use the system several times as shown in Fig. 1. Similar shapes can be found in [3].

Also in the next example, we model the final form only roughly in the graphical input. To reduce the height of the tent, the upper arch was compressed a little bit. As a result, a kink was introduced in the beam. But this kink is not a problem and smoothened (straightened) by the active bending technique, see Fig. 15.

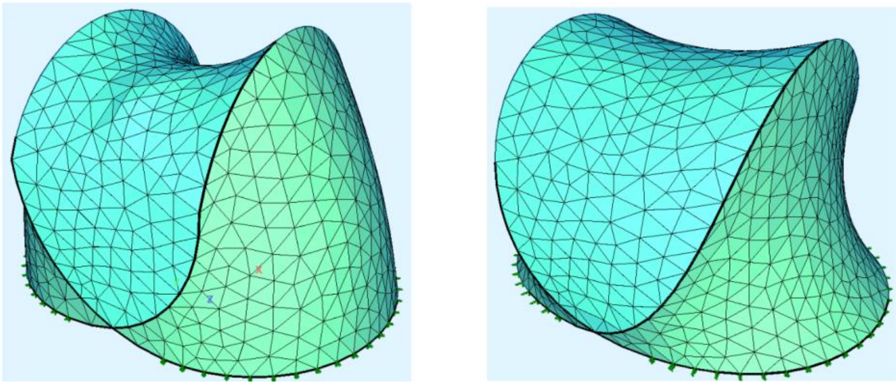

Figure 15: Throw tent: left input system, right: stressed system after ACTB active bending formfinding

With a four-node quad meshing, quads could be created at the kink with three nodes attached to an active bending beam, one node before the kink, one at the kink and one behind. If the active bending beam then gets nearly straight, at the kink an angle of nearly 180 degrees would be created and cause an error. Therefore, a triangle meshing is used here. As in membrane elements the nonconforming shape functions of a four-node quad are switched off, the use of triangle elements is sufficient.

Torsion: the rotation of the main active bending plane causes a slight torsion. But as the rod can nearly rotate free in the membrane pocket, the active bending beam withdraws himself as good as possible from torsion. Only in case the friction in the membrane pocket is high e.g. for a windsurf mast, a significant torsion may be induced on wind loading.

The last example of a sphere demonstrates how to reach various final shapes with different prestress input, see Fig. 16. Here no torsion appears in the building stage. The bending always acts in one plane. Vertical to this plane no shear force appears (disregarding of little gravity loading in the upper plane).

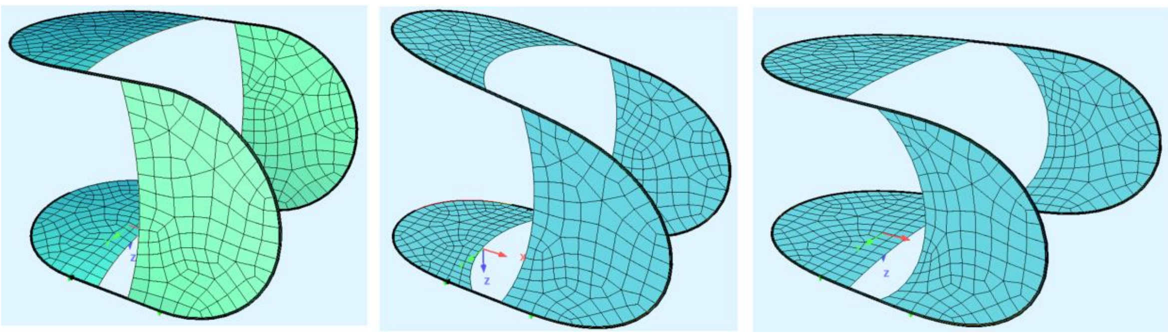

Figure 16: Spere : left input system, middle: upper areas prestressed higher, right : vertical areas stressed higher

5 CONCLUSIONS

On various examples a simple technique for creating finite element active bending beams has been represented. It is shown that in most cases it is difficult to introduce a significant torsional bending in an active bending structure.

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